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# Harvested area gaps in China between 1981 and 2010: effects of climatic and land management factors

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## Harvested area gaps in China between 1981 and 2010: effects of climatic and land management factors

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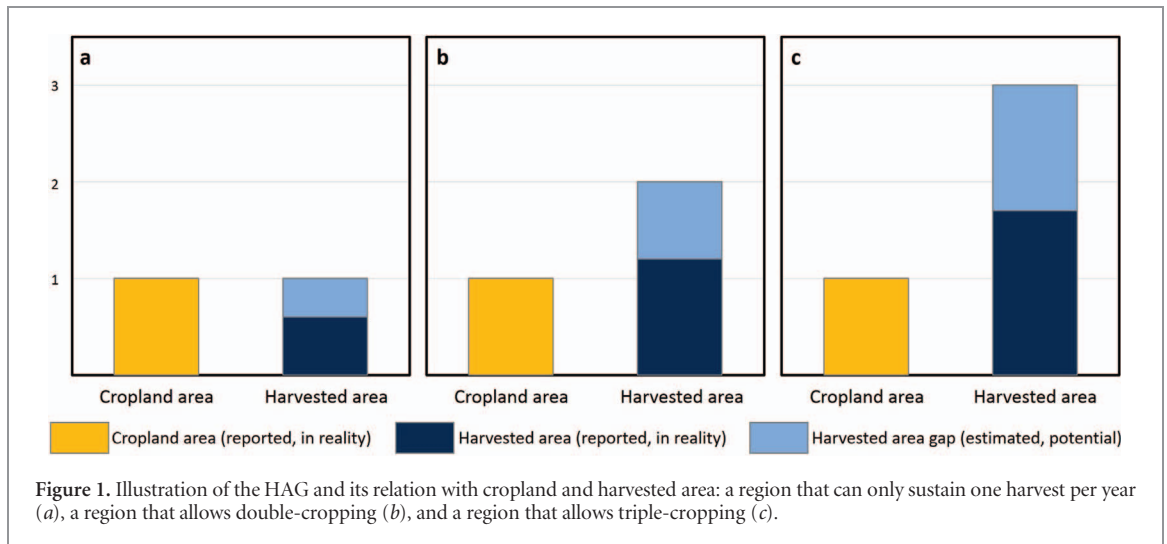
E-mail: [yuqiangyi@caas.cn](mailto:yuqiangyi@caas.cn) and [wuwenbin@caas.cn](mailto:wuwenbin@caas.cn)**Keywords:** land use change, multiple cropping, cropping frequency, food security, land use intensity, climate changeSupplementary material for this article is available [online](#)**Abstract**

Previous analyses have shown that cropland in China is intensifying, leading to an increase in crop production. However, these output measures leave the potential for further intensification largely unassessed. This study uses the harvested area gap (HAG), which expresses the amount of harvested area that can be gained if all existing cropland is harvested as frequently as possible, according to their potential limit for multi-cropping. Specifically, we calculate the HAG and changes in the HAG in China between 1981 and 2010. We further assess how climatic and land management factors affect these changes. We find that in China the HAG decreases between the 1980s and the 1990s, and subsequently increases between the 1990s and the 2000s, resulting in a small net increase for the entire study period. The initial decrease in the HAG is the result of an increase in the average multi-cropping index throughout the country, which is larger than the increase in the potential multi-cropping index as a result of the changed climatic factors. The subsequent increase in the HAG is the result of a decrease in average multi-cropping index throughout the country, in combination with a stagnant potential. Despite the overall increase in harvested area in China, many regions, e.g. Northeast and Lower Yangtze, are characterized by an increased HAG, indicating their potential for further increasing the multi-cropping index. The study demonstrates the application of the HAG as a method to identify areas where the harvested area can increase to increase crop production, which is currently underexplored in scientific literature.

**1. Introduction**

The state of food insecurity in the world has been alleviated in the recent years (IFPRI 2016), along with improved global cereal production prospects (FAO 2017). Yet, there are still an estimated 795 million people in the world that suffer from chronic undernourishment, indicating a clear need for further improving food security (FAO 2015). Although undernourishment is largely a problem of access to food, the production of enough food remains a prerequisite (Yu *et al* 2012). The necessity to increase food production is being exacerbated by the expected increase in global

food demand, which could be anywhere between 59%–98% until 2050 (Valin *et al* 2014). There are basically two options to increase food production: expansion of agricultural land and intensification of lands that are already used for agricultural production. Since we inhabit a world in which most of the fertile land has already been used (Ellis *et al* 2013, Eitelberg *et al* 2015), there is only a limited opportunity for further increases in food production from agricultural expansion (Smith 2013). Therefore, agricultural intensification as a way to increase food production has received a considerable amount of attention recently (Garnett *et al* 2013, Godfray and Garnett 2014, Struik and Kuyper 2014).



Generally, agricultural intensification in a location depends on the biophysical conditions that determine the maximum potential production and the human activities that explore such potential. A number of assessments have already quantified the opportunities for agricultural intensification, mostly by calculating ‘crop yield gaps’ (Mueller *et al* 2012, van Ittersum *et al* 2013). These empirical analyses tend to agree that changes in the biophysical conditions, especially climate change, have negative impacts on yield potential (Challinor *et al* 2014, Rosenzweig *et al* 2014), while on the other hand, yields are stagnating around the world (Ray *et al* 2012). This suggests that the pathway for further intensification by closing yield gaps is challenging. Another opportunity to increase food production is to increase the harvested area, on existing croplands by increasing harvest frequency. Multi-cropping practices and the potential of increasing multi-cropping have been investigated for a number of regions, including China (Yan *et al* 2014, Zuo *et al* 2014), the US (Seifert and Lobell 2015), Brazil (Cohn *et al* 2016), the European continent (Estel *et al* 2016, Niedertscheider *et al* 2016), and the globe (Ray and Foley 2013, Zabel *et al* 2014). Yet, the relation between multi-cropping potential and harvested area often remains unexplored, leaving the potential for further intensification through the increase of harvested area unaddressed.

In this study, we use the harvested area gap (HAG)—the difference between the potential harvested area and the actual harvested area in a region—as a measure to express the relation between the multi-cropping potential and the actual harvests (Yu *et al* 2017a). As harvested area is one of the important components of land management and thus land use intensity (Erb *et al* 2013), the HAG indicates the potential for further intensification in a region, in terms of further increasing the harvest frequency. A previous study found that the HAG in China was between 13.50 and 36.30 million hectare, depending on the water management conditions (Yu *et al* 2017a). However, this previous

study did not address temporal dynamics in the HAG. The aim of this study is to quantify changes in the HAG in China between 1981 and 2010. In addition, we assess the contribution of changes in climatic factors, expressed through the potential for multi-cropping, and changes in land management practices, reflected in the actual multi-cropping index.

## 2. Methods

### 2.1. The harvested area gap

The HAG has been introduced in Yu *et al* (2017b) and indicates the harvested area that could possibly be available when the existing cropland in a region is harvested as frequently as possible according to their potential limit for multi-cropping (figure 1). Given the required days to maturity (Asseng *et al* 2011), the possibility of increasing the harvest frequency largely depends on local climatic conditions. For staple crops, single-, double-, and triple- cropping systems are found across the globe, while quadruple-cropping systems are rare, because climatic conditions are usually insufficient to sustain four harvests in one year and because most crops require a longer period to grow (Qiu *et al* 2003, Biradar and Xiao 2011, Plourde *et al* 2013).

The HAG is defined as the difference between the potential harvested area ( $HA_p$ ) and the actual harvested area ( $HA$ ). The potential harvested area is again a function of the potential multi-cropping intensity (PMCI) and the total cropland area (CL):

$$HAG = HA_p - HA \quad (1)$$

$$HA_p = PMCI \times CL. \quad (2)$$

In these definitions, cropland area refers to the land area that is dedicated to crop production. Harvested area indicates the area that is harvested in any given year. The harvested area can be higher than the total cropland area due to multiple cropping cycles within

one year (see figure 1). Usually, both cropland and harvested area are reported on a yearly basis, and independent from each other. Dividing the harvested area by the cropland area yields the actual multi-cropping index (MCI) in a region. The PMCI, on the other hand, cannot be observed, and is therefore typically estimated based on local biophysical conditions. Under normal conditions, MCI will be lower than PMCI and HA will be smaller than  $HA_p$ , for example because of fallow land in crop rotation schemes and crop failures. Exceptions can occur if there has a large share of very short growing season crops, or as a result of technological measures to remove some of the constraints posed by climatic factors and thus allow to artificially increase the PMCI. For example, the use of agricultural plastic films (Liu *et al* 2014), could cause such effects. Our study focuses on normal, conventional and rainfed crop production, and therefore, potentially negative HAG values are set to zero. This is consistent with the concept of HAG, as no negative gaps can theoretically exist.

Both MCI and PMCI in this study express national or county-level averages. Therefore, neither MCI nor PMCI is restricted to integer values, as some fields in a county can have single cropping, while other fields have double cropping. For example, a PMCI of 1.5 could indicate that on average three crops can be grown in two years in this county, or a mixture of single-cropping parcels and double-cropping parcels. In this respect, the interpretation of MCI and PMCI is different from the number of harvests at a field level in a particular year, which is by definition an integer value.

## 2.2. Data and application

We calculated the HAG and the changes therein for a period of three decades (i.e. 1981–2010). The starting point coincides with the moment China adopted a nation-wide land-use policy (i.e. Household Responsibility System) to stimulate agricultural production (Li and Wang 2003), which overlaps with a period where climatic factors began to change (Piao *et al* 2010). A flowchart of the analysis is shown in figure 2. Because PMCI is dependent only on temperature and precipitation in this study, we refer to the contribution of changes in PMCI as changes in climatic factors (CLIMATE) from hereon. Similarly, as CL and HA are the result of human land management decisions, and are the measures for land use intensity (Erb *et al* 2013), we refer to the contribution of changes in either land management factors (LANDMGT) from hereon.

### 2.2.1. Potential multi-cropping intensity

The PMCI in China ranges between 1 in the north (one-crop a year) to 3 in the south (three-crops a year) (Liu *et al* 2013, Yang *et al* 2015), depending on the local biophysical conditions. The main determinants are temperature (Yang *et al* 2015) and precipitation (He *et al* 2016). In this study we calculate the PMCI as a function of temperature and precipitation only, while ignoring other factors that could also affect the

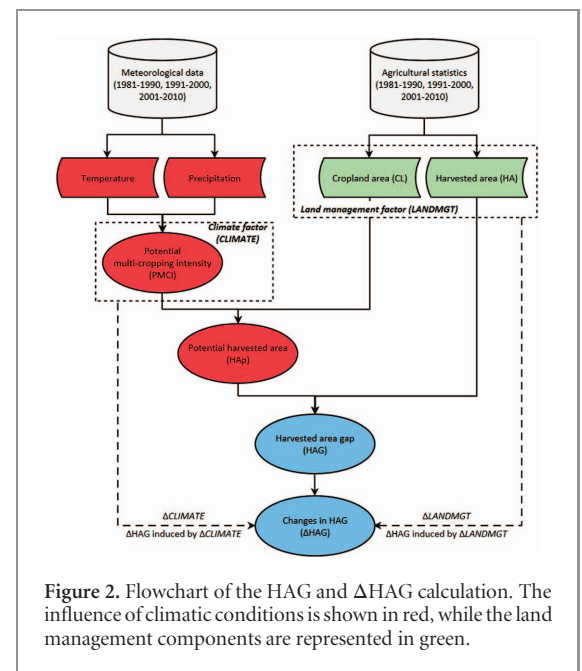


Figure 2. Flowchart of the HAG and  $\Delta$ HAG calculation. The influence of climatic conditions is shown in red, while the land management components are represented in green.

PMCI, such as soil properties or irrigation infrastructure (Liu *et al* 2013). This approach is justified because the main focus of this paper is on the changes in the HAG, and thus also PMCI over time. Climatic variables such as temperature and precipitation changed in the study period, while soils and other biophysical properties remained relative stable.

In the literature, several techniques for estimating PMCI are found, most of which are based on climatic factors. In some studies, the estimated PMCI are integer numbers, i.e. 1, 2, and 3, to roughly determine whether the region is single-cropping, double-cropping, or triple-cropping, respectively (Yang *et al* 2015). In some other studies, PMCI are floating numbers ranging between 1 and 3, which indicate average values for a larger spatial unit and over multiple years (Fan and Wu 2004). In this study, however, we applied the latter approach to PMCI, as it allows for the analysis of small and nuanced changes over time. Conversely, Yu *et al* (2017b) applied the former meaning of PMCI in their estimation of HAG in China for the year 2005. Specifically, the ‘temperature-precipitation’ model (He *et al* 2016) is applied to calculate the PMCI based on temperature and precipitation data. In this method, the PMCI is calculated as the minimum of  $PMCI_T$  and  $PMCI_P$ , which represent the temperature-limited and precipitation-limited PMCI respectively:

$$PMCI = \min(PMCI_T, PMCI_P). \quad (3)$$

According to empirical evidence (Fan and Wu 2004), a piecewise linear function was parameterized to estimate the  $PMCI_T$ . Four threshold values (i.e. 3400 °C, 4200 °C, 5200 °C, 6200 °C) are set to characterize the temperature potential for multi-cropping

in China:

$$\text{PMCI}_T = \begin{cases} 1, & T < 3400 \\ (T - 3400) \times 0.00125 & 3400 \leq T < 4200 \\ +1, 2, & 4200 \leq T < 5200 \\ (T - 5200) \times 0.001 & 5200 \leq T < 6200 \\ +2, 3, & T \geq 6200 \end{cases} \quad (4)$$

where  $T$  represents the average annual accumulated temperature ( $^{\circ}\text{C}$ ). Given unavailability of data in growing degree days, we used the annual accumulated temperature, calculated as the sum of 24 hour daily averages.

Subsequently, a continuous linear function was used to estimate the  $\text{PMCI}_P$ :

$$\text{PMCI}_P = \begin{cases} 1, & P < 500 \\ (P - 500) \times 0.00142 & 500 \leq P < 1200 \\ +2, 3, & P \geq 1200 \end{cases} \quad (5)$$

where  $P$  indicates the average annual precipitation (mm).

The parameters for these functions are derived to calculate the long term multi-cropping potential, based on multi-year average values, rather than the multi-cropping potential within a single year (Fan and Wu 2004). Hence these values are valid only for long-term analyses, rather than assessing the influence of year-to-year fluctuations. A similar approach is also adopted by Liu *et al* (2013) and Yang *et al* (2015) in their estimations. The relation between precipitation and temperature, respectively, and the PMCI are illustrated in figure S1 in the supplementary information available at [stacks.iop.org/ERL/13/044006/mmedia](http://stacks.iop.org/ERL/13/044006/mmedia). Data for the PMCI calculation are interpolated based on the daily observations at 824 meteorological stations across China, maintained by the China Meteorological Data Service Center (<http://data.cma.cn/en>).

To allow for a comparison between MCI and PMCI, a national/regional average of PMCI is calculated by dividing the sum of county level potential harvested areas (equaling the PMCI for the county multiplied by the county cropland area) by the national/regional cropland area:

$$\begin{aligned} \text{PMCI}_{\text{nation/region}} &= \frac{\sum \text{PMCI}_i \times \text{CL}_i}{\sum \text{CL}_i} \\ &= \frac{\text{HA}_{\text{P nation/region}}}{\text{CL}_{\text{nation/region}}} \end{aligned} \quad (6)$$

### 2.2.2. Cropland and harvested area

Yearly values for cropland area and harvested area for all counties in China are obtained from the Ministry of Agriculture (<http://region.agridata.cn/>). Values for both are reported, typically based on agricultural censuses. For both statistics, a complete time series is unavailable for all counties during the entire study period, mainly due to changes in administration or other unknown reasons. Interpolation and

extrapolation are therefore applied to fill data gaps prior to the analysis, based on the closest known values in time and space.

### 2.2.3. HAG and $\Delta\text{HAG}$

We calculated the HAG for each decade in our study period (i.e. 1981–1990, 1991–2000, and 2001–2010). We used decadal averages because effects of climatic variation on land management are typically not observed immediately (Reidsma *et al* 2010). Moreover, the data on cropland area and harvested area—although available at a yearly basis—show variation due to fallow land and multi-year crop rotation schemes. This could yield year-to-year fluctuations that are inherent to land management strategies while not reflecting any changes therein (Yu *et al* 2017a). The estimated HAG for the periods 1981–1990, 1991–2000, and 2001–2010 are referred to as  $\text{HAG}_{80\text{s}}$ ,  $\text{HAG}_{90\text{s}}$ , and  $\text{HAG}_{00\text{s}}$ , respectively. Consequently, the changes of HAG between two decades are expressed as:

$$\Delta\text{HAG} = \text{HAG}_{t_{n+1}} - \text{HAG}_{t_n}. \quad (7)$$

Subsequently, we analyzed the contribution of changes in climatic factors and land management factors on the HAG for each interval separately. Given the conceptualization of HAG as a direct function of PMCI and MCI we can attribute changes to climate and management likewise. Because the changes in HAG are directly affected by either CLIMATE or LANDMGT, two dummy variables are introduced, to assess the effect of each component over time separately:

$$\text{CLIMATE\_HAG}_{t_{n+1}} = \text{PMCI}_{t_{n+1}} \times \text{CL}_{t_n} - \text{HA}_{t_n} \quad (8)$$

$$\text{LANDMGT\_HAG}_{t_{n+1}} = \text{PMCI}_{t_n} \times \text{CL}_{t_{n+1}} - \text{HA}_{t_{n+1}} \quad (9)$$

where:  $\text{CLIMATE\_HAG}_{T_{n+1}}$  and  $\text{LANDMGT\_HAG}_{T_{n+1}}$  indicates the estimated HAG in  $t_{n+1}$ , when only one factor changes while the other is kept constant at the  $t_n$  values. Consequently, the CLIMATE- and LANDMGT- induced  $\Delta\text{HAG}$  between two time intervals are quantified as:

$$\Delta\text{CLIMATE\_HAG} = \text{CLIMATE\_HAG}_{t_{n+1}} - \text{HAG}_{t_n} \quad (10)$$

$$\Delta\text{LANDMGT\_HAG} = \text{LANDMGT\_HAG}_{t_{n+1}} - \text{HAG}_{t_n}. \quad (11)$$

These equations can be further transformed as:

$$\begin{aligned} \Delta\text{CLIMATE\_HAG} &= (\text{PMCI}_{t_{n+1}} \times \text{CL}_{t_n} - \text{HA}_{t_n}) \\ &\quad - (\text{PMCI}_{t_n} \times \text{CL}_{t_n} - \text{HA}_{t_n}) = \Delta\text{PMCI} \times \text{CL}_{t_n} \end{aligned} \quad (12)$$

$$\begin{aligned} \Delta\text{LANDMGT\_HAG} &= (\text{PMCI}_{t_n} \times \text{CL}_{t_{n+1}} - \text{HA}_{t_{n+1}}) \\ &\quad - (\text{PMCI}_{t_n} \times \text{CL}_{t_n} - \text{HA}_{t_n}) = \Delta\text{CL} \times \text{PMCI}_{t_n} \\ &\quad - \Delta\text{HA} \end{aligned} \quad (13)$$



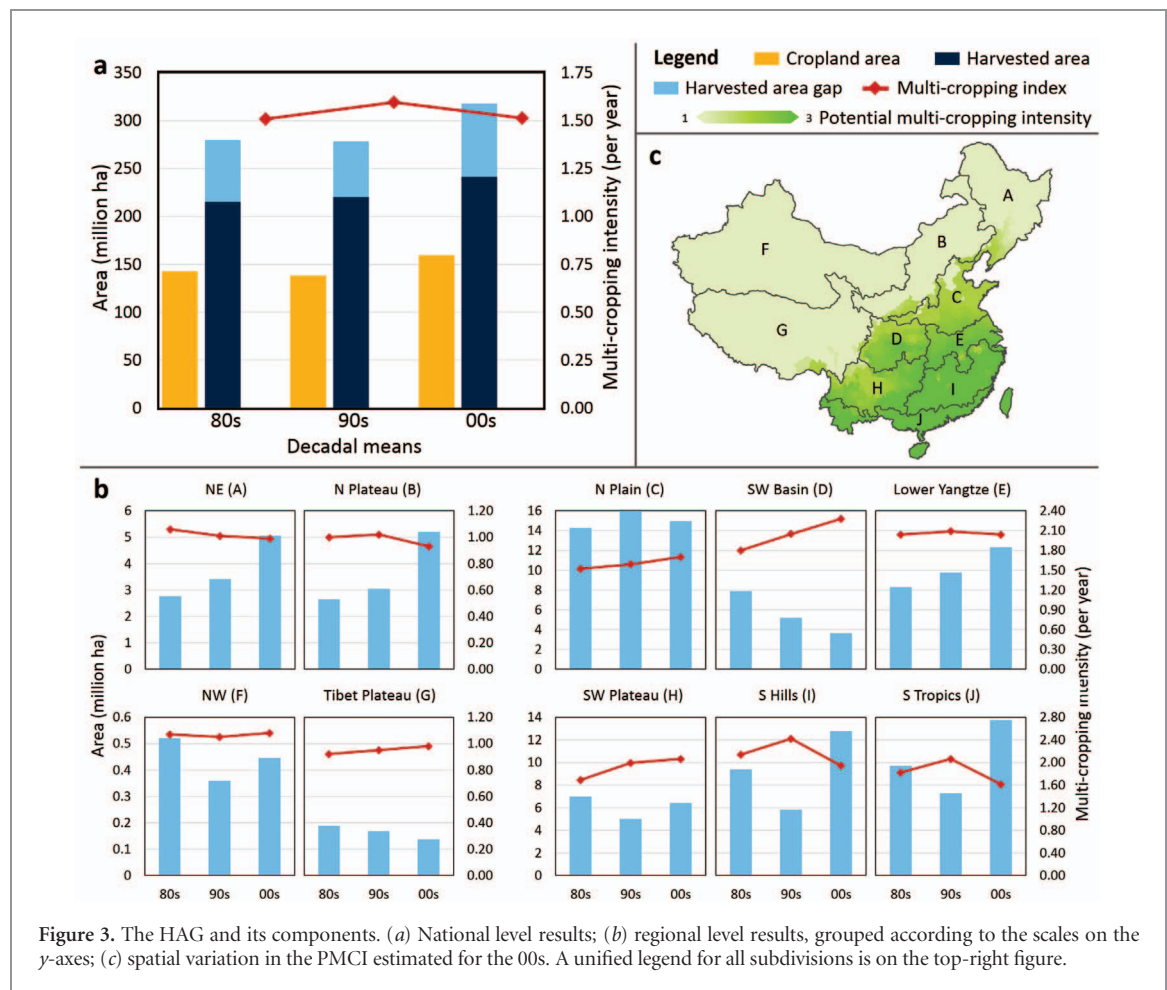


Figure 3. The HAG and its components. (a) National level results; (b) regional level results, grouped according to the scales on the y-axes; (c) spatial variation in the PMCI estimated for the 00s. A unified legend for all subdivisions is on the top-right figure.

where  $\Delta\text{PMCI}$ ,  $\Delta\text{CL}$ , and  $\Delta\text{HA}$  indicates the changes in potential multi-cropping intensity, cropland area, and harvested area in between two time intervals, respectively. The calculation of both dummy variables helps to assess the contribution of CLIMATE or LAND-MGT, respectively. Formula (12) indicates that an increase in the PMCI would lead to an increase in the HAG, everything else being equal. Formula (13) indicates that an increase in cropland area or a decrease in harvested area would result an increased HAG.

### 3. Results

#### 3.1. Estimation of the HAG in China in 1981–2010

At the national level, the estimated HAGs are 64.66 million ha, 58.07 million ha, and 76.73 million ha, in the 80s, 90s, and 00s respectively (see table 1 and figure 3(a)). However, at the regional level we find large differences in which also the direction of change differs markedly. Between the 80s and the 90s, despite a decrease in the HAG at the national level, several regions with an increased HAG are found, notably in the NE, N Plateau, and N Plain. Between the 90s and 00s, we found a HAG increase in most regions, as well as for all of China combined. For the complete study period, the HAG displays an increasing trend at the national level, with the SW

Basin as a notable exception. The detailed regional level results are presented in table 1, and their patterns are further illustrated in figure 3(b).

At the county level, results show that between the 80s and the 90s most counties saw a decrease in HAG, except some regions in the N Plain and Lower Yangtze (figure 4(a)). However, this trend was mostly reversed between the 90s and 00s: many counties have an increased HAG, and these increases are found throughout the country. The counties in the N Plain that saw an increase in HAG in the first period, are characterized by a opposite change in the second period. Yet, the counties in the Lower Yangtze that also have an HAG increase in the first period, did not see an opposite development in the second period (figure 4(b)).

#### 3.2. Factors contributing to the $\Delta\text{HAG}$

At the national level, between the 80s and the 90s, climatic factors resulted an increase in PMCI, which contributed to a gross increase in HAG. At the same time, the intensified land management contributed to an increase in the MCI and thus a gross decrease in HAG. Both effects together resulted in a net HAG decrease, suggesting that land use activities followed the enlarged climate potential (table 2). Between the 90s and the 00s, climatic factors continued to contribute to an increase in PMCI and thus also

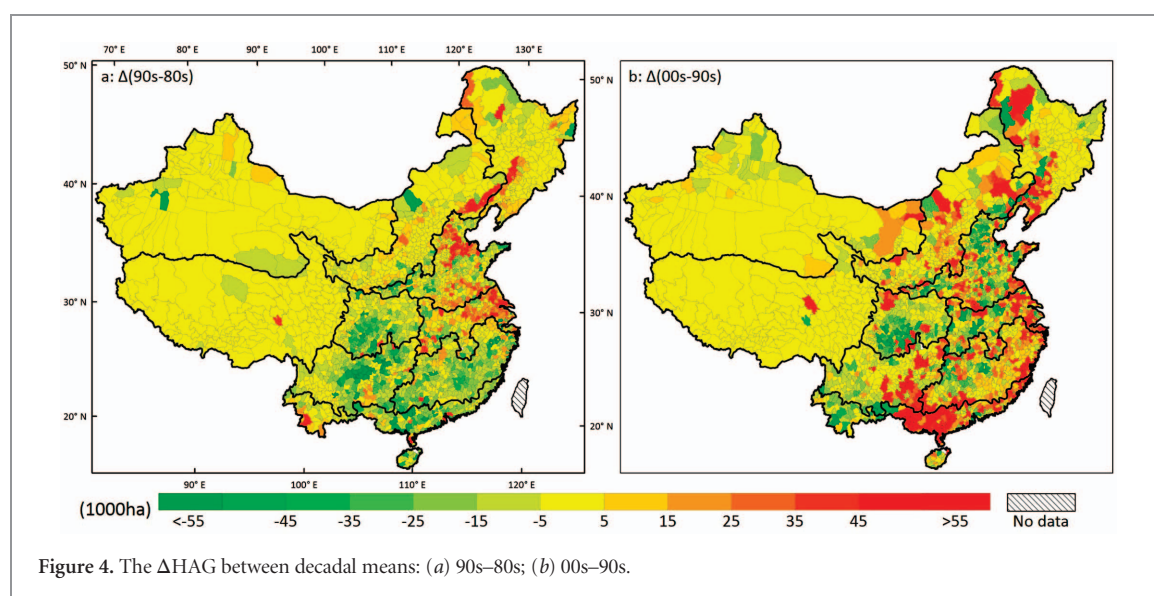
**Table 1.** The HAG at the national/regional level in the 80s, 90s, and 00s, and the changes between decadal means (unit: million ha).

Cropping regions	80s	90s	00s	$\Delta(90s-80s)$	$\Delta(00s-90s)$	$\Delta(00s-80s)$
(1) NE	2.76	3.41	5.05	0.65 (+23.6%)	1.64 (+48.3%)	2.29 (+83.2%)
(2) N Plateau	2.65	3.05	5.21	0.40 (+15.2%)	2.15 (+70.5%)	2.56 (+96.4%)
(3) N Plain	14.28	16.00	14.94	1.73 (+12.1%)	-1.06 (-6.6%)	0.67 (+4.7%)
(4) SW Basin	7.91	5.18	3.63	-2.73 (-34.5%)	-1.55 (-30.0%)	-4.28 (-54.1%)
(5) Lower Yangtze	8.29	9.79	12.35	1.49 (+18.0%)	2.56 (+26.2%)	4.05 (+48.9%)
(6) NW	0.52	0.36	0.45	-0.16 (-31.1%)	0.09 (+24.3%)	-0.07 (+14.3%)
(7) Tibet Plateau	0.19	0.17	0.14	-0.02 (10.3%)	-0.03 (-19.0%)	-0.05 (-27.3%)
(8) SW Plateau	7.00	5.01	6.43	-1.98 (-28.4%)	1.42 (+28.2%)	-0.57 (-8.1%)
(9) S Hills	9.38	5.83	12.79	-3.56 (-37.9%)	6.97 (+119.6%)	3.41 (+36.3%)
(10) S Tropics	9.70	7.28	13.75	-2.42 (-24.9%)	6.47 (+88.9%)	4.05 (+41.8%)
<b>China</b>	<b>64.66</b>	<b>58.07</b>	<b>76.73</b>	<b>-6.58 (-10.2%)</b>	<b>18.66 (+32.1%)</b>	<b>12.07 (+18.7%)</b>

**Table 2.** The  $\Delta$ HAG and the contributions from climatic factors (CLIMATE) and land management factors (LANDMGT) (unit: million ha).

	$\Delta$ HAG (90s-80s)	CLIMATE	LANDMGT	$\Delta$ HAG (00s-90s)	CLIMATE	LANDMGT
NE	0.65	1.02	-0.26	1.64	0.15	1.48
N Plateau	0.40	0.80	-0.35	2.15	-0.27	2.80
N Plain	1.73	4.64	-2.51	-1.06	1.08	-2.62
SW Basin	-2.73	-0.24	-2.42	-1.55	0.48	-1.73
Lower Yangtze	1.49	3.09	-1.49	2.56	1.64	1.05
NW	-0.16	0.00	-0.16	0.09	0.00	0.09
Tibet Plateau	-0.02	0.00	-0.02	-0.03	0.00	-0.04
SW Plateau	-1.98	0.43	-2.22	1.42	0.39	1.22
S Hills	-3.56	0.33	-3.69	6.97	0.19	6.86
S Tropics	-2.42	0.07	-2.49	6.47	-0.03	6.49
<b>China</b>	<b>-6.58</b>	<b>10.15</b>	<b>-15.61</b>	<b>18.66</b>	<b>3.63</b>	<b>15.60</b>

Note: Because potential negative HAG values are set to zero before further processing, regional values for CLIMATE and LANDMGT might not add up to the national total (see section 2.1).

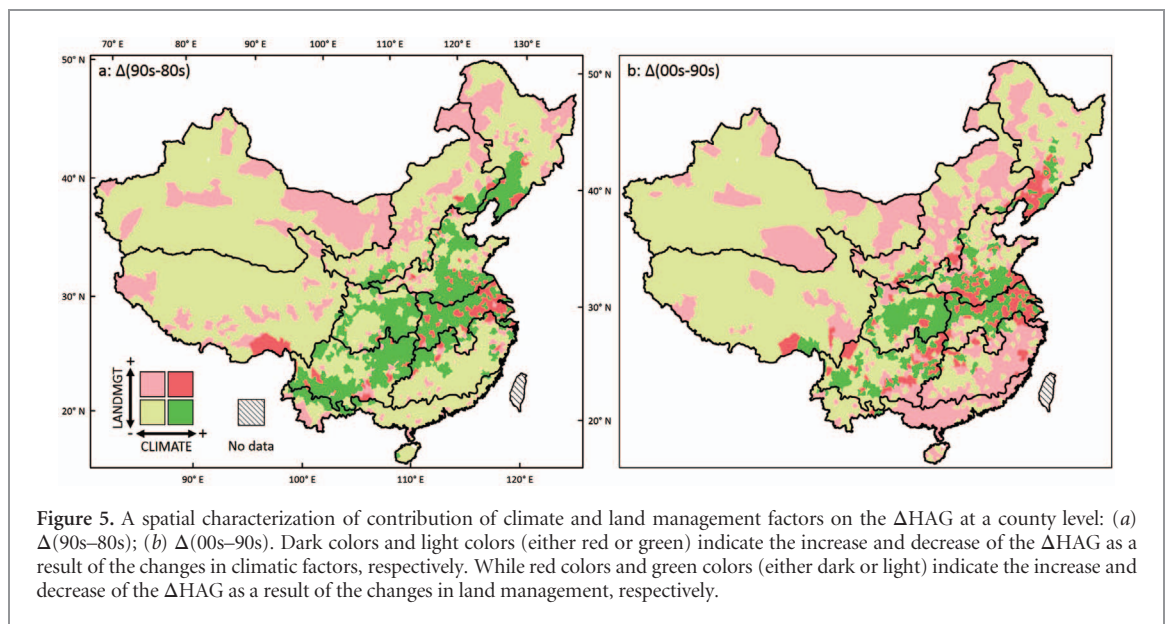


a gross increase in HAG, yet the contribution was much lower than the first period. On the other hand, we found an overall decrease in exploiting this potential, leading to net HAG increase. This suggests that land management didn't follow the increased PMCI brought by changed climatic factors in this period. This lead to an increase in the HAG at the national level (table 2).

To analyze the spatial variation in the factors underlying the  $\Delta$ HAG, we categorized them into four groups for describing the combined (positive or negative) contribution of changes in climatic and land management factors (figure 5). Between the 80s and

90s, HAG increases as a result of the changed climatic factors are concentrated in the N Plain, SW Basin, Lower Yangtze, SW Plateau, and some part from the NE (darker colors). At the same time, there are considerably more counties with dark green, indicating an increased potential as a result of the changes in climatic factors as well as increased MCI as a result of the changes in land management. This suggests that farmers in these counties have explored the change in potential by an increase in their MCI. Dark red counties, indicating an increased multi-cropping potential with a decreased MCI, were primarily found in the eastern part of the Lower Yangtze. In these counties,





the HAG increases as a result of both climate and land management changes (figure 5(a)). Between the 90s and 00s, there are less counties with darker colors, suggesting that climatic factors only increased the PMCI in a few counties. At the same time, the red colors, either dark or light, become more predominant, indicating an increase in the HAG as a result of a decrease in multi-cropping index across the country. Especially in the S Hills and S Tropics, most counties are represented with a light red, against the light green in the previous period (figure 5(b)).

## 2. Discussion

We find a strong increase in the PMCI between the 80s and the 90s, corresponding to the findings of Liu *et al* (2013) and Yang *et al* (2015). Between the 90s and the 00s, this effect is much less apparent, and even reversed in some regions. These differences can be explained as Liu *et al* (2013) consider soil as a constraint in addition to temperature and precipitation, while Yang *et al* (2015) only consider temperature. Consistently, our PMCI values are in between those reported in these two studies. Although the direction of change correspond with Liu *et al* (2013) and Yang *et al* (2015), the absolute values differ. Furthermore, we find that the HAG in China ranges between 58.07 and 76.73 million hectares between 1981 and 2010. This is on the higher side of the range of values reported by Yu *et al* (2017a) for the year 2005, as they find a HAG between 13.50 and 36.30 million hectares, by applying Yang *et al* (2015)'s estimation on PMCI and using different irrigation regimes to refine the (86.10 million hectares) temperature-determined HAG. Yet, in this study we use precipitation instead of irrigation as a water source, which therefore also yields a HAG in pixels that do not have a connection with the irrigation network, thus explaining the higher values

found in this paper. At the same time, because we assume that constraints posed by irrigation regimes existed throughout the complete study period, this simplification would not invalidate the  $\Delta$ HAG over time found in this study.

To supplement our analysis, we present the additional maps showing the reported county level values for CL and HA, and the calculated values for PMCIs, MCIs and HAGs in each period in figure S2–S4. Moreover, 10 year running averages for CL and HA data and the results of HAG at both national and regional level are available from figures S5–S6 (upper frames). The results of national and regional values for PMCIs and MCIs based on the same 10 year moving averages are also presented in figure S5–S6 (lower frames). We find that although the PMCI and MCI remain relatively stable at the national level, there are clear regional disparities. The gaps between the PMCI and the MCI are small in the NE, Lower Yangtze, comparing to a wider gap in the N Plain. SW Basin and SW Plateau are narrowing the gap gradually, while S Hills, S Tropics and N Plateau act at the opposite. The MCI is slightly higher than the PMCI in the region NW, which suggests that the calculated PMCI is not correctly representing the maximum potential. This could be due to the uncertainty that is inherent to the climatic data interpolation and the underlying method, but it is unlikely that such uncertainty would yield a systematic error for such a large area. However, it could also suggest that our PMCI calculation is not fully applicable to local cropping systems. One potential explanation is the application of technology, such as greenhouses, which artificially removes some of the climatic constraints of the area (figure S6). Moreover, the PMCI was calculated for distinct cropping cycles of a 'typical average crop'. Hence short cropping cycles, as well as intercropping, which does not allow distinct crop cycles, could result in a MCI that is higher than the estimated PMCI. As a consequence, the real PMCI

might be higher than our calculated PMCI, and as a consequence, the HAG values we found might underestimate the actual potential for increasing the harvested area. Yet, by presuming the ‘typical average cases’ are predominant across China, we assume that these limitations do not invalidate the results of this study. However, due to the lack of gridded meteorological, greenhouse agriculture, and crop distribution/sequence data, these uncertainties cannot be well quantified.

We further analyzed the yearly variations of MCI, PMCI and HAG within each decade. We find that PMCI shows little variation across years in all regions except for the N Plain (figure S7). As large variation was observed in all three periods, it might reflect inherent properties of variation in the climatic conditions of that region. Moreover, the variation in PMCI is larger than in MCI at the national level (figure S7(d) and figure S8(d)), suggesting that farmers do not follow the year-to-year variation observed in climatic conditions, but instead keep their land management rather stable as compared to the environmental variations. This confirms our assumption that farmers’ multi-cropping decisions rely on long-term average climatic conditions rather than year-to-year fluctuations, showing risk averse decision-making (Reidsma *et al* 2010). It also implies that farmers can not foresee the evolvement of the cropping season before sowing and therefore can only react to long-term trends. However, there is no clear correlation among variations of MCI, PMCI, and HAG (figure S9) at the national level. For instance, large differences are found in the patterns in the Northeast. Although we have no more detailed explanation of this finding, this may be caused by non-simultaneous changes in MCI and PMCI that lead to a greater change in HAG.

These results indicate that adaptation of land management to climate change is complicated: responses to climate change are not linear and increased opportunities provided by climate change do not necessarily result in land use intensification. Seifert and Lobell (2015) analyzed how changes in suitability for double cropping yielded adaptation to climate change by 2100 in the United States. They indicated that a considerable expansion of double cropping can be anticipated under future climate change. However, our results for China suggest that such simplifications may not always hold: the changes between the 90s and 00s show an increase in the HAG and a decrease in MCI (see figure 3(a)), while the overall PMCI increased as a result of the changes in climatic variables during this period. There are multiple processes that can potentially explain these results. For example, the observations could be a reaction on earlier increases in MCI, suggesting these were an over-reaction to the increased opportunities provided by climate change. At the same time, changes in water availability or other considerations related to land management could have played a role as well. Moreover, small increases

in PMCI do not necessarily allow a full additional crop or are not fit to the crops preferred in a certain area or the specific crop cultivar and rotation applied (Hu *et al* 2017, Tito *et al* 2017). Therefore, further analysis of when and how farmers increase the MCI would be of particular interest for future studies, as well as in-depth assessments of other management decisions towards increasing land use intensity, that might confound the relation between PMCI and MCI. For example, figure 4 shows that many regions with an increasing HAG are close to the urban metropolises, e.g. Beijing, Shanghai and in the industrialized South. This could suggest that the increase in HAG is related to a lack of labor to take advantage of the increased PMCI, as, the massive rural-urban migration in China has increased off-farm employment and reduced the availability of rural labor in recent decades. Furthermore, although the stress of food demand has remained, China has increased its food import from other countries, which could translate into a lower demand for domestic food, and thus less pressure to close the HAG. Site-specific and long-term observations at the field level would provide opportunities for better understanding the interactive process of land management adaptation to climate change (Yu *et al* 2017b).

A wide range of indicators, including labor, fertilizer, pesticides, irrigation water, cropland area, harvested area, multi-cropping index, etc have been used to characterize land use intensity (Erb *et al* 2013). Yet most of these focus on the land use intensity itself while leaving the potential for further intensification unassessed. Our paper makes a contribution by analyzing the dynamics of this specific aspect of land use intensity, which is not often addressed. Specifically, the continued increase of harvested area, as presented in our study, could be seen as an indication that China is intensifying its land use. However, our study also finds that while the harvested area increased in many regions, the potential to further intensification also increased in the same period. These results suggest that a rather nuanced approach is required when interpreting land use intensity and especially the changes therein. Similarly, Pires *et al* (2016) recently showed that climate risk is increasing in Brazilian double cropping systems, suggesting that the future prospects of maintaining land use intensity requires investigation, along with measuring intensity itself.

### 3. Conclusions

In this paper, we analyze the  $\Delta$ HAG in China between 1981 and 2010 and we further attribute the  $\Delta$ HAG to changes in climatic and land management factors. We find that the HAG decreased from the 80s to the 90s and then increased afterwards, leading to a small net increase at the end. This suggests that despite observed increases in multi-cropping over the course of the study period, changes in climatic factors has

provided additional opportunities for intensification, yet the potential is not fully exploited and the responses of land management to climate change are not linear. The potential for future land use intensification could be focused on regions with enlarged HAG, especially for those regions where land management has contributed more gross HAG increase. Given the simplified measurement in this study, other constraints, such as soil, water, labor, climate extremes etc deserve subsequent analyses for the full exploitation of HAG in future studies.

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